Green hydrogen in India: A techno-economic and policy roadmap for decarbonization and energy transition

Beer Singh Bisht[1], Virendra Bahadur Singh[1], and Ajay Kumar[1]

ABSTRACT

India's shift toward a sustainable energy future positions green hydrogen at the heart of its decarbonization strategy. Produced using renewable energy sources like solar and wind, green hydrogen offers a clean alternative for reducing emissions in hard-to-abate sectors. The launch of the National Green Hydrogen Mission (NGHM) in 2023 marks a significant step forward, aiming to produce 5 million tonnes of green hydrogen annually by 2030. This paper analyses the techno-economic feasibility of green hydrogen in India, focusing on production costs, advancements in electrolyser technologies, and the evolving policy landscape. It evaluates the potential for green hydrogen integration in key sectors such as steel, transportation, and refining, i.e., industries where deep emission cuts are essential. Despite its promise, large-scale deployment of green hydrogen in India faces significant challenges, including high capital costs, limited infrastructure, and evolving technology readiness. The study emphasizes the role of government incentives, industry partnerships, and global collaborations in overcoming these barriers. India's abundant renewable resources and strong policy backing offer a competitive advantage. Achieving cost parity with grey hydrogen is essential for large-scale adoption. The paper concludes with strategic recommendations to accelerate research and development (R&D), expand infrastructure, and establish regulatory frameworks to ensure green hydrogen's long-term viability.

KEYWORDS

Green hydrogen, net zero, decarbonization, energy transition, Renewable energy

INTRODUCTION

India's economic growth is closely linked to its energy consumption. As the world's most populous country and one of its fastest-growing major economies, India's demand for energy is projected to surge in the coming decades. Traditionally, this demand has been met largely by fossil fuels, making India the third-largest emitter of greenhouse gases (GHGs) globally (after China and USA). However, in recent years, India has demonstrated a strong commitment to climate action, culminating in the ambitious "Panchamrit" pledge at United Nations Framework Convention on Climate Change (UNFCCC), which includes a target of achieving net-zero emissions by 2070 and sourcing 500 GW of its electricity from non-fossil fuel sources by 2030 (Government of India, 2023).

Achieving these targets requires a transformative shift in India's energy landscape. While the power sector is rapidly decarbonizing through the expansion of solar and wind power, several key areas of the economy, such as steel, cement, long-haul freight, shipping, petrochemicals, transport, oil-refining and aviation, remain difficult to decarbonize through direct electrification. These 'hard-to-abate' sectors require high-density energy carriers and chemical feedstocks that are currently derived from fossil fuels. Green hydrogen has emerged as a promising and versatile alternative to this challenge (RMI, 2022). Figure 1 illustrates the green hydrogen production process. It is produced through the electrolysis of water, a process powered by renewable energy, resulting in zero carbon emissions.

Green hydrogen can be used as a clean fuel, an energy storage medium, and a feedstock for producing green ammonia and other synthetic fuels. Recognizing this potential, the Government of India launched NGHM in January 2023, with an initial outlay of ₹19,744 crore (approximately USD 2.4 billion). The mission sets an ambitious target of achieving 5 million metric tonnes (MMT) of green hydrogen production annually by 2030, supported with about 125 GW of renewable energy capacity (MNRE, 2023).

This paper presents a critical overview of India's emerging hydrogen economy, emphasizing technological advancements, policy frameworks, and the systemic challenges associated with scaling up green hydrogen production, storage, and distribution infrastructure.

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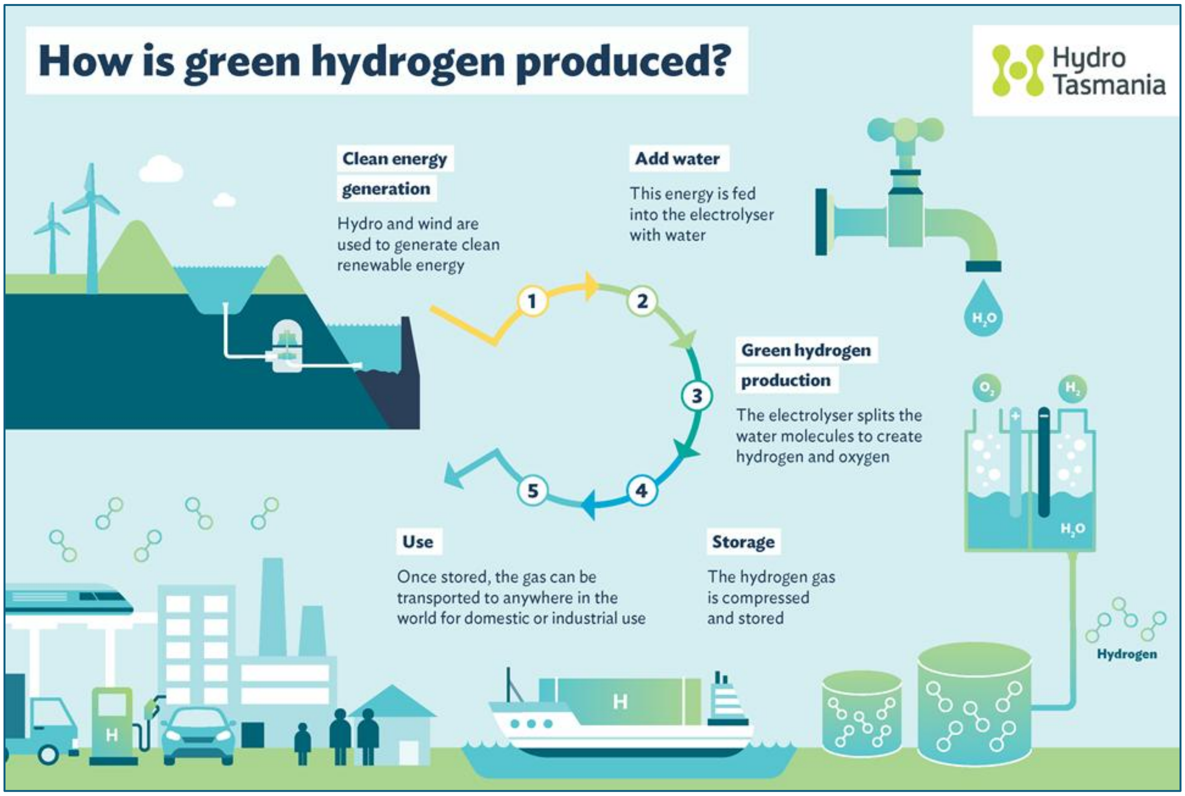

Figure 1: *Process of green hydrogen production: renewable energy, electrolysis, storage, and transportation for global usage. (Source: https://www.hydro.com.au/clean-energy/hydrogen)*

AREA OF STUDY: HYDROGEN'S ROLE IN INDIA'S ENERGY TRANSITION

India currently consumes more than 6 MMT of hydrogen annually, (Jha, 2021) the majority of which is produced from fossil fuel-based processes such as natural gas reforming. This results in substantial greenhouse gas emissions, necessitating the decarbonization of hydrogen production. Figure 2 categorizes hydrogen types by technology, feedstock source, and associated greenhouse gas emissions.

Green hydrogen, produced via electrolysis powered by renewable energy sources, offers a carbon-free alternative. It is increasingly viewed as a key enabler for decarbonizing hard-to-abate sectors like steel, refining, and fertiliser production.

As illustrated in Figure 3, global hydrogen production is expected to grow significantly between 2025 and 2050. By mid-century, green hydrogen produced through dedicated renewable electrolysis is projected to dominate the global hydrogen mix. This shift aligns with India's commitment under the National Green Hydrogen Mission, which aims to position the country as a leading producer and exporter of green hydrogen. In contrast, fossil-based hydrogen with carbon capture (blue) is expected to play a more limited role, while grid-connected electrolysis (yellow) could serve as a transitional solution. This projected trajectory highlights India's pursuit of clean energy and energy independence.

Hydrogen presents an opportunity for India to address multiple challenges in its energy and industrial landscape:

- *Decarbonization of heavy industries:* Hydrogen can play a crucial role in decarbonizing hard-to-abate sectors like steel, cement, and petrochemicals, where electrification is less feasible.
- *Energy security:* Hydrogen can reduce India's reliance on imported fossil fuels, enhancing energy

<table>
<tr><th>Terminology</th><th>Technology</th><th>Feedstock/electricity source</th><th>GHG footprint</th></tr>
<tr><td>Green hydrogen</td><td rowspan="2">Electrolysis</td><td>Wind | solar | hydro | geothermal | tidal</td><td rowspan="2">Minimal</td></tr>
<tr><td>Purple/pink hydrogen</td><td>Nuclear</td></tr>
<tr><td>Yellow hydrogen</td><td>Natural gas reforming + CCUS Gasification + CCUS</td><td>Mixed-origin grid energy</td><td>Medium</td></tr>
<tr><td>Blue hydrogen</td><td>Natural gas</td><td>Natural gas | coal</td><td>Low</td></tr>
<tr><td>Turquoise hydrogen</td><td>Natural gas reforming</td><td rowspan="2">Brown coal (lignite)</td><td>Solid carbon (by-product)</td></tr>
<tr><td>Brown hydrogen</td><td>Gasification</td><td>High</td></tr>
<tr><td>Black hydrogen</td><td>Gasification</td><td>Black coal</td><td>High</td></tr>
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***Figure 2**: Different types of hydrogen compared by production method, source, and GHG footprint.*

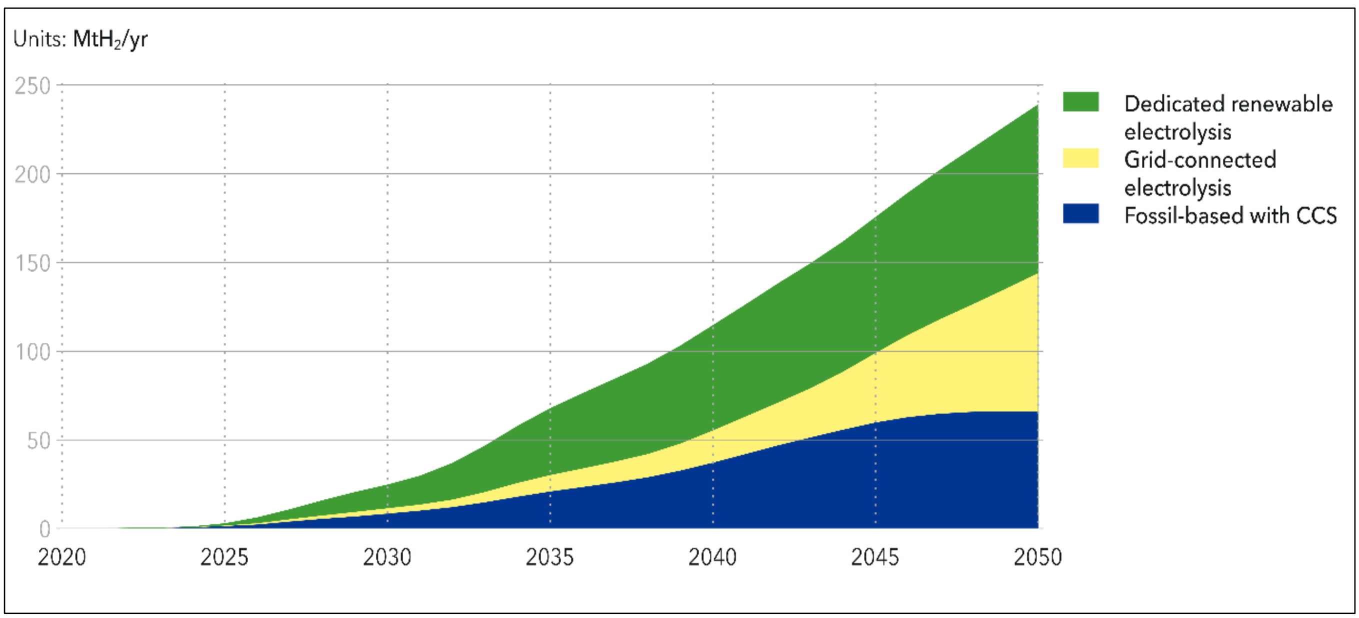

***Figure 3**: Global hydrogen production growth by technology, 2025-2050 projections (Reina, 2022)*

- security. By investing in domestic hydrogen production, India can insulate itself from global energy markets volatility.
- *Transport sector:* Hydrogen fuel cell electric vehicles (FCEVs) offer a promising alternative to battery electric vehicles (BEVs) for long-haul transport, heavy-duty vehicles, and public transportation, which are sectors where battery solutions may face limitations in range, weight, or refueling time.
- *Grid stability and storage***:** Hydrogen can act as a storage medium for excess renewable energy, helping stabilize the grid and enabling a continuous energy supply even when renewable generation is low.

GOVERNMENT INITIATIVES AND POLICY SUPPORT

For establishing a robust green hydrogen ecosystem, the Indian government has undertaken several strategic policy interventions. The cornerstone of this effort is the **NGHM** launched in 2023, which aims to produce 5 MMT of green hydrogen annually by 2030. It provides financial incentives for both electrolyser manufacturing and hydrogen production through schemes like the Strategic Interventions for Green Hydrogen Transition (SIGHT). To reduce import dependency and lower costs, dedicated funds have been allocated to support domestic electrolyser manufacturing. The mission also emphasizes **R&D** to enhance production technologies and promotes the creation of enabling infrastructure such as pipelines and hydrogen refueling stations. Furthermore, the policy focuses on deploying green hydrogen in hard-to-abate sectors like steel, transport, and shipping, areas where conventional electrification faces limitations. Collectively, these measures aim to accelerate India's transition towards a low-carbon hydrogen economy while boosting industrial innovation and energy security.

CURRENT STATUS OF HYDROGEN PRODUCTION IN INDIA

India is currently in the nascent stages of hydrogen production, with the majority of hydrogen being produced from natural gas through steam methane reforming, commonly referred to as grey hydrogen. This form of hydrogen is mainly consumed in the refining and fertilizer sectors. However, in pursuit of its climate goals and net-zero commitment by 2070, the Indian government is prioritizing the transition to green hydrogen, which is produced using renewable energy sources and emits zero carbon. To enable this transition, the National Hydrogen Energy Mission (NHEM) launched in 2021, outlines a strategic framework for hydrogen production, infrastructure development, and export potential. The mission targets the production of 5 million tons of green hydrogen annually by 2030. Several pilot projects (Table 1) have already been initiated to decarbonize core sectors such as steel, ammonia, mobility, and power generation. These projects aim to validate the technical and economic feasibility of green hydrogen at scale in India.

Both NGHM and NHEM are key initiatives aimed at leveraging hydrogen as a clean energy carrier, though they differ in focus and scope. NGHM seeks to position India as a global hub for the production, utilization, and export of green hydrogen and its derivatives. Its primary goals include decarbonization, reducing dependence on fossil fuel imports, and fostering a sustainable energy system. In contrast, NHEM emphasizes integrating hydrogen into India's energy mix by linking the country's expanding renewable energy capacity with the hydrogen economy. Mission will assist in domestic demand creation, encourage incentive schemes and programmes and will facilitate export opportunities through supportive policies and strategic partnerships. The mission will identify and develop regions capable of supporting large scale production and/or utilization of hydrogen as green hydrogen hubs.

These pilots are crucial to building the hydrogen ecosystem, reducing emissions in hard-to-abate sectors, and laying the groundwork for large-scale deployment.

CHALLENGES IN SCALING HYDROGEN IN INDIA

India's ambition to scale hydrogen as a cornerstone of its clean energy transition is hindered by multiple challenges. The foremost issue is the high production cost of green hydrogen, which remains less competitive than grey or blue hydrogen due to expensive electrolyser and limited renewable energy infrastructure. Moreover, India lacks a nationwide hydrogen ecosystem comprising adequate production facilities, transport pipelines, storage systems, and refuelling stations, especially for sectors like mobility and heavy industry. Technological gaps persist, with ongoing R&D required to enhance the efficiency and cost-effectiveness of electrolyser and fuel cells. Additionally, a comprehensive and consistent policy and regulatory framework is still evolving, with unclear guidelines on incentives, subsidies, and carbon pricing. Furthermore, hydrogen's highly flammable nature raises safety concerns, necessitating the development of stringent safety protocols for its production, storage, and distribution. Addressing these multidimensional challenges is essential for enabling a scalable, secure, and economically viable hydrogen economy in India.

Table-1: India's green hydrogen pilot projects across sectors: key players and outcomes.

Sector	Project description	Expected outcomes	Key players	Financial data
Steel	Green hydrogen is being piloted to replace coal in steel production, aiming for low-emission steel manufacturing	Reduce emissions in the steel industry, particularly in direct reduced iron (DRI) processes.	Public and private steel firms, government incentives.	Government covering up to 50%-70% of CAPEX, depending on project scale. Total investment: ₹300-500 crore.
Shipping	Hydrogen bunkering and refuelling stations are being set up to retrofit ships to use hydrogen as fuel.	Demonstrate the feasibility of hydrogen as a maritime fuel, reducing shipping emissions.	Shipping corporation of India, port authorities.	Government providing ₹200 crore in CAPEX for retrofitting and refueling infrastructure. Developers bear hydrogen production costs.
Transport	Hydrogen-powered buses, trucks, and other vehicles are being tested in select cities and highways.	Showcase green hydrogen's potential to decarbonize the transport sector, especially heavy-duty vehicles.	Various state government, private vehicle manufacturers.	Approximately ₹800 crore allocated for hydrogen-powered vehicles and refuelling stations under National Green Hydrogen Mission.
Ammonia production	A project focused on producing green ammonia using hydrogen for fertilizers.	Reduce carbon footprint in ammonia production, a major hydrogen consumer.	Fertilizer companies, renewable energy firms.	CAPEX projected at ₹400-600 crore for initial phase. Partial government funding via NGHM and private investments.
Refineries	Green hydrogen is being used in refineries to reduce carbon emissions during oil refining.	Lower emissions in refinery operations, which are significant hydrogen users.	Indian Oil Corporations, HPCL.	Estimated ₹1,000 crore for retrofitting refineries to use green hydrogen. Funding shared between private sector and government.

POLICY INITIATIVES AND SUPPORT FOR HYDROGEN DEVELOPMENT

India is strategically promoting hydrogen as a key pillar of its clean energy transition, with the NGHM 2023 outlining ambitious targets. However, its successful implementation depends on strong policy support. Key measures include providing incentives for green hydrogen production—such as subsidies for renewable energy integration, electrolyser manufacturing, and dedicated R&D efforts—which are essential to lower production costs. Implementing carbon pricing mechanisms and emissions regulations can make hydrogen more competitive by reflecting the true cost of carbon emissions. Public-private partnerships (PPP) will play a vital role in developing infrastructure, fostering technological advancements, and attracting investments. Furthermore, India is actively engaging with countries like Japan, Australia, and Germany to strengthen international collaboration, enabling knowledge transfer and joint ventures in hydrogen technologies. A comprehensive and coordinated policy framework is crucial to scale up hydrogen adoption and achieve India's long-term energy and climate goals.

TECHNO-ECONOMIC ANALYSIS OF GREEN HYDROGEN

The economic viability of green hydrogen is the most critical factor determining its large-scale adoption. The levelized cost of hydrogen (LCOH) is a function of several variables, primarily the cost of renewable electricity, the capital expenditure (CAPEX) on electrolyser, and the electrolyser's utilization factor.

Production technologies

The primary technology for green hydrogen production is water electrolysis. The three main types of electrolysers are:

- *Alkaline Electrolysers (AEL):* This is a mature and commercially available technology with lower capital costs. However, it has a lower current density and a slower response to the intermittency of renewable power compared to PEM electrolysers.
- *Proton Exchange Membrane (PEM) electrolysers:* PEM technology offers higher efficiency, a smaller footprint, and a faster dynamic response, making it well-suited for integration with variable renewable energy sources like solar and wind. The main drawback is its higher cost, primarily due to the use of platinum-group metals as catalysts.
- *Solid Oxide Electrolyser Cells (SOEC):* This is an emerging technology that operates at high temperatures, offering the potential for very high efficiency, especially when integrated with industrial heat sources. However, it is still in the early stages of commercialization.

India's strategy, under the NGHM's SIGHT programme, is to support the domestic manufacturing of both AEL and PEM electrolysers through production-linked incentive (PLI) schemes (Law, 2024).

Cost dynamics and projections

The cost of green hydrogen production in India is currently estimated to be in the range of ₹320-400/kg (USD 3.9-4.8/kg), which is significantly higher than the cost of grey hydrogen (produced from natural gas) at around ₹160/kg (USD 1.9/kg) (KPMG, 2022). The cost structure of green hydrogen is dominated by the cost of renewable electricity, which accounts for 50-70% of the total production cost (Figure 4).

However, India has a significant advantage in this regard. The cost of solar and wind power in India is among the lowest in the world, with tariffs for solar power reaching as low as ₹2.1/kWh (RMI, 2024). As renewable energy costs continue to decline and electrolyser manufacturing is scaled up, the cost of green hydrogen is projected to fall significantly (Table 2).

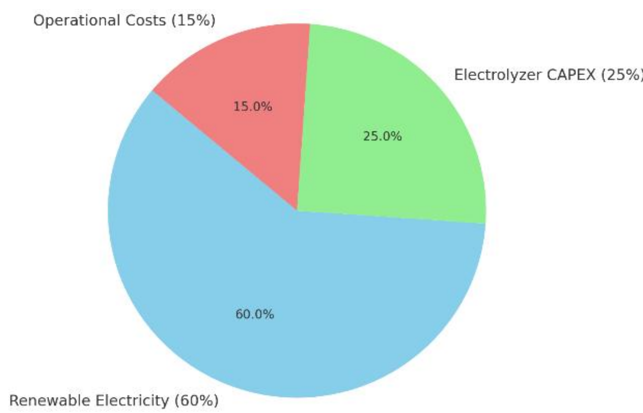

Figure 4: *Cost components of green hydrogen production.*

The optimistic scenario assumes a rapid decline in renewable energy and electrolyser costs, coupled with high utilization factors achieved through hybrid renewable energy systems (solar and wind) and supportive grid policies. By 2030, under this scenario, green hydrogen could achieve cost parity with grey hydrogen, unlocking widespread adoption.

Table-2: *Projected cost of green hydrogen in India (USD/kg)*

(Source: Synthesized from NITI Aayog (2022) and CEEW (2023) projections)

Year	Optimistic scenario	Pessimistic scenario
2025	3.5	4.5
2030	1.8	2.5
2040	1.2	1.8
2050	0.8	1.2

Market demand and applications

The potential demand for green hydrogen is vast, particularly in key sectors such as steel production, refineries, and transportation:

- *Steel industry:* Transitioning to green hydrogen could significantly reduce emissions in the steel sector, which currently relies heavily on coal. The International Energy Agency (IEA) (www.iea.org) estimates that hydrogen could replace around *25% of the current hydrogen demand* used in steelmaking.
- *Refineries:* The refining sector is another substantial market for green hydrogen, with significant emissions reduction potential. By integrating green hydrogen, refineries can produce cleaner fuels and comply with stringent emission regulations.
- *Transportation:* As hydrogen fuel cell technology matures, the transport sector, especially heavy-duty vehicles and shipping, represents an emerging market. The demand for hydrogen refuelling infrastructure will also grow, supported by government initiatives.

Long-term market impact

The adoption of green hydrogen is expected to have profound implications for India's energy market. The green hydrogen market is projected to attract substantial investments, with estimates suggesting that the Indian green hydrogen economy could be worth US$19 billion by 2030 (Reina, 2022). This investment influx will not only facilitate technology development but also spur job creation in manufacturing, R&D, and infrastructure development.

Investing in green hydrogen can diversify India's economy by reducing its dependency on fossil fuel imports. By becoming a leader in hydrogen production, India can enhance its energy security and foster resilience against global energy price fluctuations. The transition to green hydrogen will contribute significantly to India's emissions reduction targets. It is estimated that by adopting green hydrogen, India can mitigate around 1 billion tonnes of CO_2 emissions annually by 2030, a commitment made during the COP26 summit in Glasgow (COP26). This transition not only aids in achieving national targets but also aligns with global climate commitments under the Paris Agreement.

CONCLUSIONS

Green hydrogen presents a transformative opportunity for India to achieve its decarbonization goals and ensure long-term energy security. As the country progresses toward its 2030 targets under NGHM, scaling up green hydrogen production will be critical, particularly for reducing emissions in hard-to-abate sectors. However, despite its potential, several challenges remain. Techno-economic assessments highlight key barriers such as high production costs, limited infrastructure, and existing technological limitations. Nevertheless, India's vast renewable energy resources, supported by strategic policy interventions, targeted financial incentives, and expanding international collaborations, provide a strong foundation to overcome these hurdles. Achieving cost parity with grey hydrogen by 2030 will be vital to unlocking the full potential of green hydrogen. This will require substantial investment in research and development, rapid scaling of electrolyser manufacturing, and accelerated deployment of renewable energy infrastructure.

The development of a robust hydrogen infrastructure, covering storage, transportation, and distribution, is critical to facilitating the large-scale deployment of green hydrogen. Strong public-private partnerships, supported by clear and enabling regulatory frameworks, will play a vital role in driving innovation, enhancing investor confidence, and stimulating market demand. By capitalizing on its abundant renewable energy resources and aligning policy initiatives with industrial objectives, India is well-positioned to emerge as a global leader in the green hydrogen economy.

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BIOGRAPHIES

Prof. Beer Singh Bisht has a master's degree in physics form Indian University and is an experienced professional with over 35 years of distinguished service in the leading National Oil Company (ONGC) in India, where he held the prestigious position of Group General Manager. Throughout his career, he played a pivotal role in the exploration, production, and strategic management of oil and gas assets, contributing significantly to the growth and modernization of the energy sector in India. An accomplished technocrat, Prof. Bisht has presented numerous technical papers at renowned international conferences and forums, earning him recognition from global peers for his insights and innovations in hydrocarbon exploration and reservoir management. His expertise spans upstream operations, policy formulation, team leadership, and implementation of cutting-edge technologies in oil and gas development. After his services in the corporate sector, Prof. Bisht transitioned to academia and is currently serving as Professor at the reputed Graphic Era University, Dehradun. In his academic role, he continues to inspire and mentor the next generation of engineers and geoscientists, bridging industry experience with academic excellence.

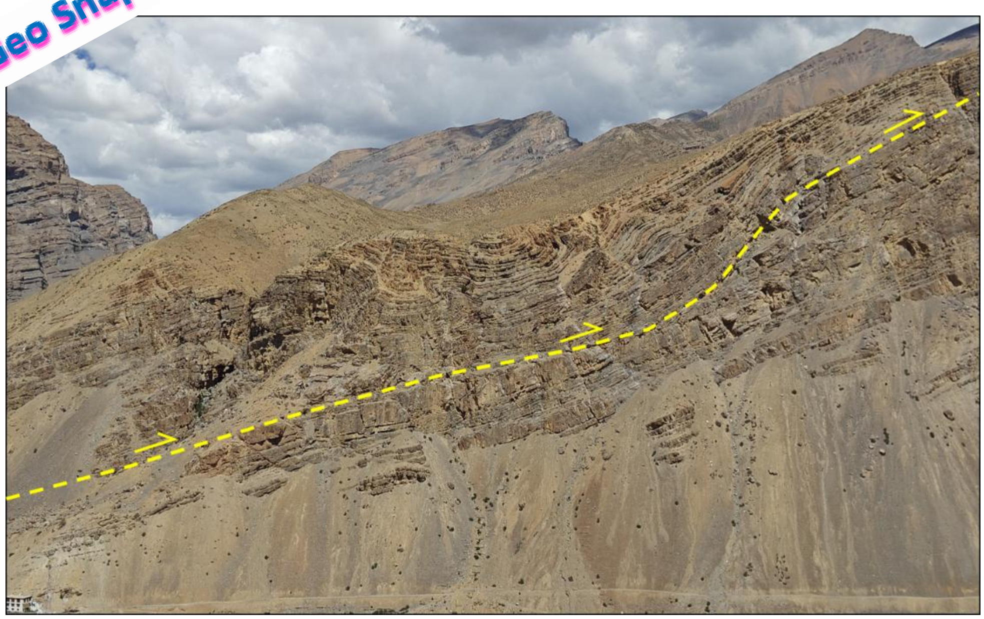
Prof. Virendra Bahadur Singh holds a distinguished academic background, with a Postgraduate Diploma in Computer Science, an M.Sc. in applied geology, and a D.Phil. from the University of Allahabad, India. He has also qualified national-level examinations such as the NET-CSIR and GATE. His academic excellence has been recognized through prestigious awards including the Senior Research Fellowship from CSIR, New Delhi, and the Fast Track Scheme for Young Scientists from Science and Engineering Research Board, Department of Science and Technology, New Delhi. He currently serves as Professor and Head of the Department of Petroleum Engineering and Earth Sciences at Graphic Era (Deemed to be) University, which ranks among the top 50 universities in India as per the NIRF (National Institute Ranking Framework) 2025 rankings. With over two decades of experience in teaching and research, Prof. Singh has made significant contributions to education, research, and training in the fields of petroleum engineering and geosciences.

His current research focuses on subsurface evaluation using multi-proxy approaches combined with AI and ML techniques. He is an active member of several professional societies, including the Society of Petroleum Engineers (SPE) and the Indian Society of Remote Sensing (ISRS), among others. Prof. Singh is actively involved in teaching and supervising B.Tech., M.Tech., and Ph.D. students, guiding their projects and dissertations. He has authored numerous research papers and articles contributing to the advancement of his field.

Prof. Ajay Kumar is currently serving as an Assistant Professor in the Department of Petroleum Engineering and Earth Sciences at Graphic Era (Deemed to be) University, Dehradun, India. He holds a Bachelor of Engineering in Chemical Engineering from Mumbai University and an M.Tech in Chemical Engineering from the Indian Institute of Technology (IIT) Guwahati, Assam, India. He began his professional career as a Graduate Engineer Trainee (GET) at Unique Paints, Gujarat. He later joined the Department of Chemical and Petroleum Engineering at NIMS University, Jaipur, Rajasthan, where he worked from 2013 to 2017. Over the years, he has taught a wide range of core and advanced courses across chemical engineering, petroleum engineering, and earth sciences, including fluid mechanics, thermodynamics, heat and mass transfer, petroleum refining engineering, reservoir engineering, natural gas engineering, advanced enhanced oil recovery (EOR) techniques, and geochemistry.

His primary research interests lie in petroleum refining, advanced EOR mechanisms, reservoir engineering and characterization, and renewable energy, particularly biomass/biofuel conversion. Prof. Kumar is an active member of the Society of Petroleum Engineers (SPE) and holds membership in the Institution of Engineers India (IEI).

Geo Snap



Fault-bend fold and minor folds in Kioto Limestone near Lalung, Spiti-Zanskar Basin.

(Photo courtesy: Syed Shadab Ahmed and Deepak Rawat, ONGC)